

# Current Research in Fluid Mechanics

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Since Sir James Lighthill wrote the above essay “What is Mechanics?” for the first edition of this book, fluid mechanics, like solid mechanics, has seen remarkably rapid growth and evolution. In part this stems from the needs of industry and government and from the needs of other sciences such as biology, physics and earth sciences (for example). Whatever the application, every new problem requires the development of new fluid mechanics, on account of the nonlinearity and intrinsic complexity of the governing Navier-Stokes equations. However, the principal change over the last thirty years has been the totally unpredicted explosion in the computing power available. Theoreticians have been able to simulate larger and larger fluid systems, with ever-increasing resolution and accuracy, using Computational Fluid Dynamics (CFD) to explore and supplement mathematical models in regions of parameter space for which mathematical analysis is impractical. At the same time the enhancement of computer power has permitted new, non-invasive imaging technology and the ability to visualise complete flow fields (at least in the laboratory) from massive quantities of data. Examples of newly developed methods include Ultra-sound Doppler Velocimetry, Laser Doppler Velocimetry, Particle Image Velocimetry and Magnetic Resonance Imaging. A little more detail on some areas is given below.

**Multiphase Flows.** This topic includes bubbles (of gases in liquids), drops (of liquids in gases), flow of liquids and/or gases in porous media, flow of gases and liquids together in pipes, suspensions of small solid or fluid particles in liquids, flow of granular media, and the mechanics of foams. Surface tension forces are often dominant, and the Marangoni stresses generated by thermal or solutal gradients in surface tension may also be important. The break-up into drops of a cylindrical jet,

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whose instability has been known since Lord Rayleigh in the 19th century, can now be both visualised and simulated with unprecedented resolution in both time and space. The flow and instability of thin liquid films, as on the inside of pipes (in a chemical plant or the lungs, say) or between rollers in the manufacture of steel sheets, plastic films or paper, has become a recognised subject in its own right. It is both practically important and attractive to applied mathematicians because the governing equations can be reduced in order by use of the lubrication approximation. The flow of granular media, in which the contact forces between the grains dominate the fluid dynamical forces, has also become a lively subject in its own right.

**Non-Newtonian Fluid Dynamics.** In classical fluid dynamics the fluid is in general Newtonian, the deviatoric stress tensor being directly proportional to the strain rate tensor; the constant of proportionality (twice the viscosity) may depend on temperature or solute concentration, but not on strain rate. However, many everyday fluids are non-Newtonian, being shear-thinning, shear-thickening or viscoelastic. This is typically because the fluid is a solution of large molecules (e.g. a polymer) or a suspension of colloid particles, and the scientific concern is twofold: what is the constitutive relation between stress and strain rate that should replace the Newtonian relation, and what are the consequences for the flow patterns and the forces exerted on solid boundaries? As in many fields, understanding the macroscopic properties of the fluid from a mechanistic description of its microstructure (molecules or particles and their interaction) is a problem of fundamental importance and great difficulty. Continuum modelling of granular media is particularly difficult when the grains are irregular, and the gap between experimental data and theoretical or computational prediction remains wide.

**Microhydrodynamics.** When the Reynolds number is small, so that inertia is negligible, the Navier-Stokes equations reduce to the Stokes equations. These equations are linear, but nevertheless the field of microhydrodynamics has continued to be a rich source of both interesting problems and physical understanding. There are perhaps three principal sources of interest: the need for microscopic understanding of concentrated colloidal suspensions, as discussed above; the many microfluidic devices currently being developed under the somewhat misleading title of ‘nanotechnology’; and the desire to understand the locomotion and interaction of swimming micro-organisms. The study of internal flows, in cells or vesicles, driven by active molecules or external stresses, is another subfield.

**Biological Fluid Dynamics.** As Lighthill has pointed out, this subject can be subdivided into external fluid dynamics—the interaction between living organisms and their fluid environment—and internal, physiological fluid dynamics. In the former category comes both low-Reynolds-number locomotion of micro-organisms and high-Reynolds-number swimming of fish and cetaceans, flying of birds, bats and insects, filter feeding, deformation of plants by ambient flow, etc. In physiology the interest remains primarily in the circulation of the blood, airflow in the lungs, and the flow of other ‘biofluids’. Large computational and experimental programmes have been developed to compute the flow and wall shear stress in the complex 3D geometries of arteries and airways, obtained by imaging of individual

subjects, as aids to diagnosis and treatment, and with a view to optimising prosthetic devices such as artificial heart valve and stents.

Like other fields, biological fluid dynamics has changed its focus over the years, from being a source of nice problems that lead to new physical understanding of fluid dynamical processes, to being an essential component in developing new biological understanding of how plants and animals work. This can only be done in close association with biological experiments, and these too require totally novel quantitative experimental techniques, often at the cellular or subcellular level.

**Flow-Structure Interactions (FSI).** The study of blood flow in elastic vessels is just one area in which dynamic interaction between the fluid flow and solid deformation is important. Biology yields numerous examples of FSI in which the structures are soft. The more traditional fields of aeronautical or mechanical engineering continue to yield a rich diversity of FSI problems with stiff structures—structural stability, flutter, aeroacoustics—that need to be solved in the relevant industries.

**Geophysical and Environmental Fluid Dynamics (GEFD).** Laboratory experiments on rotating and stratified fluids have been successfully performed and understood theoretically. The problem with extending that understanding to the terrestrial scale—oceans and atmosphere—or larger lies in the difficulty of achieving enough observational data. Satellite imaging using radiation of various wavelengths (not just visible light) means that coverage of the atmosphere, especially where it contains particles or water droplets, and of the surface layer of the ocean, is now extensive, so that the spatial resolution is just about adequate for four or five day computed weather forecasts. However, data at depth in the ocean are still sparse, and prediction of ocean behaviour remains an uncertain science.

A major interest in GEFD is in stirring and mixing, from the point of view both of controlling pollution and of understanding the supply of nutrients to biological organisms in the ocean. Regions of high solute and particle concentration are advected with the ambient flow, but are sheared by velocity gradients, so high concentration gradients develop laterally, permitting diffusive mixing. This, together with the desire to understand turbulence, is one motivation behind the development of vortex dynamics and topological fluid dynamics as a separate subfield of fluid mechanics.

**Hydrodynamic Instability and Transition to Turbulence** are topics that have interested fluid dynamicists for over 150 years, and continue to occupy many of us. Every topic referred to above gives rise to stability problems, which are treated using traditional linear and weakly nonlinear methods as well as Direct Numerical Simulation. One exciting development in particular concerns the transition to turbulence in unidirectional (or nearly so) flows in pipes and boundary layers. Stimulated by remarkably precise experiments on pipe flow, there has been an extremely fruitful symbiosis between CFD and dynamical systems theory, in which exact travelling-wave solutions of the Navier-Stokes equations are regarded as unstable fixed points in the space of all solutions, around which the trajectory of the actual solution can be understood. Research on turbulence itself continues to

occupy many researchers, but even with modern computer power DNS still cannot simulate turbulence at Reynolds numbers of practical importance!

The above omits all mention of many central and long-standing areas of fluid mechanics, such as the effects of compressibility, or chemical reactions (e.g. in combustion), or heat transfer, or water waves, or magnetohydrodynamics, for example, but it is hoped that the limited survey may be seen as a representative snapshot of current research in fluid mechanics.

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